DEVELOPMENT OF ADAPTIVE AUTORECLOSURE ALGORITHM IN TRANSMISSION LINES

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Abstract

Autoreclosure provides a means of improving power transmitting ability and system stability. The conventional reclosure adopts the fixed dead time interval strategy, that is, the reclosure is activated after a time delay to restore the system to normal as quickly as possible without regard to the system conditions; however, these simple techniques cannot give the optimal operating performance. For this reason, various adaptive reclosure algorithms have been proposed until now. The variable dead time control algorithm is able to ascertain the secondary arc extinction time and distinguish a permanent fault from a transient fault using the voltage waveform. The optimal reclosing instant is the time when the transient energy of the post-reclosing system is minimum; a transient stability is maintained when reclosure is carried out at the optimal reclosing time. This paper presents an adaptive autoreclosure algorithm including the variable dead time and optimal reclosure. The reclosure algorithm performs the operations that are attuned to the power system conditions. The proposed adaptive reclosure algorithm is verified and tested using ATP/EMTP MODELS, and the simulation results show that the system oscillations are reduced by employing the proposed adaptive reclosure algorithm.

1 Introduction

Reclosures are means of increasing dependability of supply; stability must consider permanent faults and line outages as a worst case scenario. However, unsuccessful reclosure onto a permanent fault may threaten system stability and aggravate severe damage to the system and equipment. For this reason, it is very important in a reclosure sequence to distinguish a permanent fault from a transient fault. However, conventional autoreclosure techniques adopt fixed dead time interval techniques, that is, the breaker recloses as quickly as possible after a prescribed period following tripping operation regardless of whether the fault is permanent or transient. Recently, various methods for distinguishing between a permanent fault and a transient fault have been proposed [1]-[2]. Although a permanent fault can be distinguished from the transient fault and the secondary arc extinction time can be estimated by using these proposed methods, the faster dead time proposed is not necessarily better to enhance the transient stability because reclosing immediately following secondary arc extinction (in the case of a transient fault) can lower the chance of a successful reclosure; importantly, the reclosing transients can be accentuated thereby having a detrimental effect on the system. Research has shown that the optimal reclosing time is the instant when the transient energy of the post-reclosing system is minimum because the larger the transient energy the weaker is the system stability causing the system to oscillate heavily [3]-[4]. Optimal reclosure can also improve [5]-[6] the transient stability. These methods are based on a technique that reduces the impact on the system during the reclosing procedure.

This paper firstly describes two different autoreclosure schemes. The first autoreclosure scheme is based on a variable dead time control algorithm which is able to ascertain the secondary arc extinction time and distinguish a permanent fault from a transient fault using the voltage waveform of the tripped line. The second is a scheme based on optimal reclosure by using the generator angle in real-time in relation to the transient energy function (TEF). In addition, it suggests an adaptive autoreclosure algorithm as a combination of the variable dead time reclosure and optimal reclosure. Finally, the simulation results are presented and discussed. The simulation is implemented using ATP/EMTP MODELS, and the simulation results show the effectiveness of the suggested schemes.

2 Adaptive Auto Reclosing Algorithm

2.1 Fault Type and Autoreclosures

It is very important in a reclosure sequence to distinguish clearly between a permanent fault and a transient fault. The very vast majority of existing reclosure techniques do not make this distinction and as such, adopt fixed dead time interval techniques regardless of whether a fault is permanent or transient. A permanent fault poses a threat to equipment and system stability during the reclosing procedure, whereas an optimal reclosure after transient fault clearance prevents system instability and maintains the continuity of supply. In any case, a reclosure on to a permanent fault must be avoided. In this respect, conventional autoreclosing techniques adopt a fixed dead time interval policy irrespective of whether a fault is transient or permanent in nature and therefore cannot guarantee that reclosing will be successful, even though statistics show a very high percentage of faults are temporary.

In the variable dead time control scheme proposed in [1], the voltage waveform of the tripped line is used to distinguish between a permanent and a transient fault and estimates the precise secondary arc extinction time in the case of single pole auto-reclosing. It is also shown that the voltage of tripped line is increased at the time of secondary arc extinction in the transient fault. Case [2] describes the adaptive three-phase autoreclosure technique using a neural network which uses frequency bands as features, and shows that the voltage waveform, is very similar to that encountered in the single-pole reclosure technique presented in [1]; this can be directly attributed to the intercircuit mutual coupling effect associated with three-phase reclosure in double circuit lines.

In this paper, the variable dead time control scheme using voltage waveforms proposed in [1] are used to distinguish the fault types and estimate the secondary arc extinction time in the three-phase autoreclosure as well as the single-pole autoreclosure.

2.2 Optimal Reclosing Time

Generally, it is believed that the faster the line reclosing is, the better the system stability will be for a transient fault. However, the faster line reclosing may not be better for the transient stability in some cases. The optimal reclosing instant is the time when the transient energy of the post-reclosing system is minimum, because a higher transient energy weakens the system stability and increases the oscillation [4]. The transient energies of the pre-reclosing and the post-reclosing system are described, and the method of calculating the optimal reclosing time is shown in [4].

In a one machine infinite bus (OMIB), the transient energy function after a fault is given as [3,7]:

$$V_f = V_k + V_p = \frac{1}{2}M\omega^2 - P_m(\delta - \delta_s) - P_e(\cos\delta - \cos\delta_s) \qquad (1)$$

Where, V_f : transient energy after fault

V_k : kinetic energy after fault

V_p : potential energy after fault

M : inertia constant of the generator

ω : angular velocity of the generator

P_m : mechanical power input of the generator

P_e : electrical power output of the generator after fault

δ : the generator angle after fault

δ_s : stable equilibrium point after fault

The total transient energy, which is the sum of the kinetic and potential energy, remains constant after a fault, and the energy is exchanged between the kinetic and potential energy.

At the instant of pre-reclosing, the kinetic energy is:

$$V_k = V_f + P_m(\delta_{RC} - \delta_s) + P_e(\cos\delta_{RC} - \cos\delta_s) \qquad (2)$$

Where, δ_{RC} is the generator angle at the moment of the pre-reclosing.

At the instant of post-reclosing, the transient energy after the post-reclosing is written as:

$$V_{RC} = V_k - P_m(\delta_{RC} - \delta_{sRC}) - P_{eRC}(\cos\delta_{RC} - \cos\delta_{sRC}) \qquad (3)$$

Where, V_{RC} is the transient energy after reclose, P_{eRC} is the electrical power output after reclose and δ_{sRC} is the stable equilibrium point after reclose.

Substituting (2) into (3) results in:

$$\begin{aligned} V_{RC} &= V_f - P_m(\delta_s - \delta_{sRC}) - P_e\cos\delta_s + P_{eRC}\cos\delta_{sRC} \\ &\quad - (P_{eRC} - P_e)\cos\delta_{RC} \end{aligned} \qquad (4)$$

When the transient energy V_{RC} in (4) reaches its minimum, it is the optimal reclosing instant. At the instant of reclosing, the variables except for δ_{RC} are the fixed values, and V_{RC} is determined by the generator angle δ_{RC} at the instant of reclosing. In a transient fault, the electrical power output of post-reclosing P_{eRC} is usually larger than the electrical power output of pre-reclosing P_e. Therefore, V_{RC} becomes its minimum value when the absolute value of δ_{RC} is a minimum. Figs. 1(a) and 1(b) show the optimal reclosing time in the time domain and the power-angle plane, respectively.

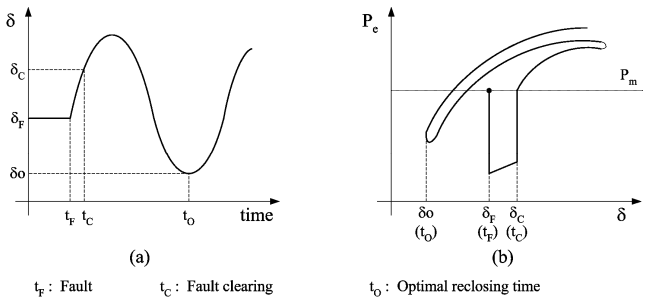

Figure 1: Optimal reclosing time in the OMIB system. (a) Time domain. (b) Power-angle plane.

As seen in Fig. 1, the optimal reclosing time is the instant when the generator angle passes its minimum and not zero; thus the optimal reclosing instant is found easily using the generator angle in the OMIB. The algorithm to find the optimal reclosing time is shown in Fig. 2. The angular velocity is calculated in block ①; here the angular velocity ω[n] is calculated by low-pass filtering of the difference-value between δ[n] and δ[n-1], and then the optimal reclosing time is deduced in block ② when the angular velocity changes the sign from negative to positive or the generator angle changes the sign from positive to negative, i.e. the generator angle passes its minimum and not zero. This method can be extended to a multimachine system using emergency EEAC whereby a multimachine system is substituted for the OMIB system, and the generator angle of the equivalent OMIB may be used to find the optimal reclosing time in Fig. 2.

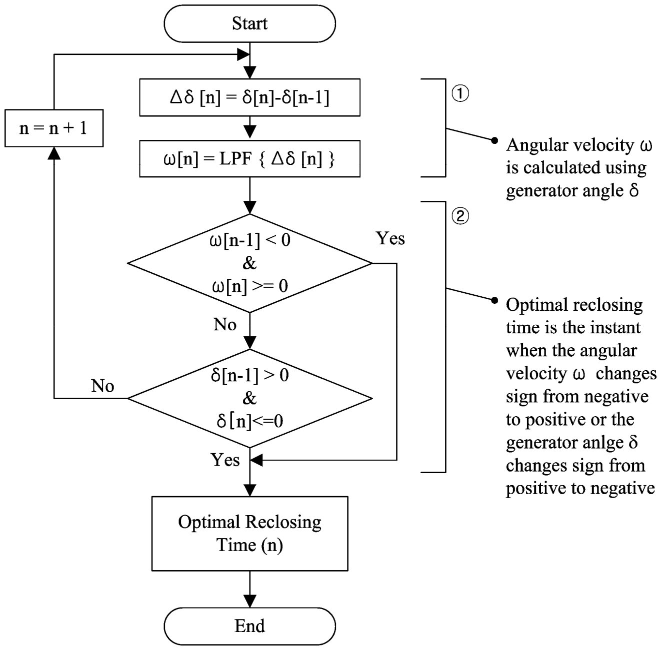

Figure 2: Flowchart to find the optimal reclosing time

2.3 Adaptive Auto Reclosing Algorithm

For the variable dead time control scheme proposed in [1], we are able to distinguish clearly between a transient and permanent fault and estimate the precise secondary arc extinction time using the voltage waveform of the tripped line. In the case of a permanent fault, the avoidance of reclosure would prevent a second shock, thereby preventing the transient stability from getting worse. However, in the case of a transient fault, the secondary arc extinction time may not be equal to the optimal reclosing time presented in section 2.2; thus the reclosing time has to be greater than the secondary arc extinction time as well as equal to the optimal reclosing time with regard to the transient stability.
This paper proposes the adaptive reclosing algorithm where the reclosing operation is changed depending on the fault type and the transient stability. If $\boldsymbol{T_V}$ is the secondary arc extinction time using the method described in section 2.1 and $\boldsymbol{T_O}$ is the optimal reclosing time described in section 2.2, the reclosure is activated when $\boldsymbol{T}$ is greater than $\boldsymbol{T_V}$ and equal to $\boldsymbol{T_O}$. The reclosure at the optimal reclosing instant enhances the transient stability.

3 Simulation and Results

3.1 Model of Power System

A set of simulation tests were performed on the test model of a 345kV power system shown in Fig. 3 [8] which is interfaced with the model of the reclosure relays implemented through ATP/EMTP MODELS, which makes it possible to simulate the interaction between the power system and the relay [9]. The transmission system modelled comprises of a total line length of 100 km; the nominal power frequency is 60 Hz. Synchronous Machine (SM) card and Transients Analysis of Control Systems (TACS) are used for governor and excitation systems of the ULCHIN nuclear power plant in Korea. For a transient fault, Johns and Aggarwal's primary arc model [1] is utilized and the secondary arc is simulated by using the simulation technique in [10]-[12].
Sample numbers per period are set to 12, and the phasor measurement units (PMUs) and the remote terminal units (RTUs) are installed at the power station of generator G1 and bus 2, where angle and active power at both G1 and bus 2 are measured and transmitted to the central equipment in real-time via the data transmission system. In the central equipment, the difference of the angle is calculated and transmitted to the reclosure relays (RCR1 and RCR2 in Fig. 3). Here, the generator angle may be obtained from the phasor measurement at the generator terminal [13]-[14].
The conventional autoreclosure relay and the adaptive autoreclosure relay which adopts the proposed optimal reclosing algorithm are simulated respectively, and their performances are compared. The conventional autoreclosure relay model employed herein is based on the technique which is adopted by Korea Electric Power Corporation (KEPCO), that is, the fixed dead time interval is set to 0.4s for three-phase reclosure, 0.8s for single-pole reclosure and the synchro-check relay setting is 30°.

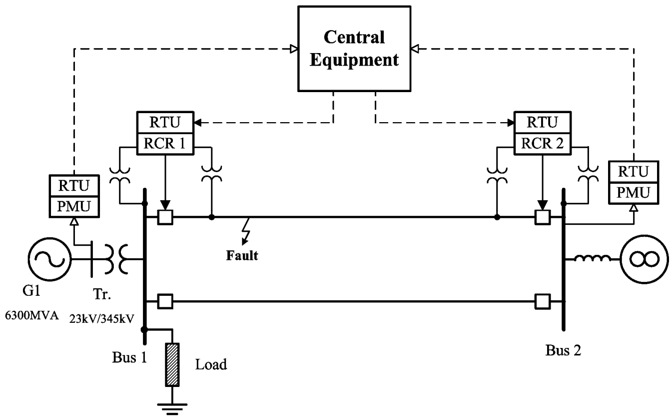

Figure 3: Model of power system (OMIB system)

3.2 Simulation Results

The conventional reclosure relay and adaptive relcosure relay adopting the algorithm of Fig. 2 are simulated; the fault considered is a double line-to-ground arcing fault, which occurs 2s after the start of the simulation at a fault distance of 5% from bus 1. The faulted line is tripped 3.5 cycles after the fault occurs, and the differences in fault clearance times on both buses are 1 cycle.
In the simulation of the adaptive reclosure relay, Fig. 4 depicts the voltage waveforms at the relay point for the transient and permanent faults. In Fig. 4, A1 is the point at which the double line-to-ground fault occurs, and the protection system detects the fault and opens three phases via the circuit breaker at point A2. In the case of a transient fault, the voltage is increased after point A3 when the secondary arc

extinguishes, thus activating the reclosure at point A4 as seen in Fig. 4(a). In marked contrast, in the case of the permanent fault, there is no increment of the voltage during the simulation as shown in Fig. 4(b), and hence the reclosure is prevented. These waveforms are very similar to the waveforms that are presented in [1] for the single-pole autoreclosure.

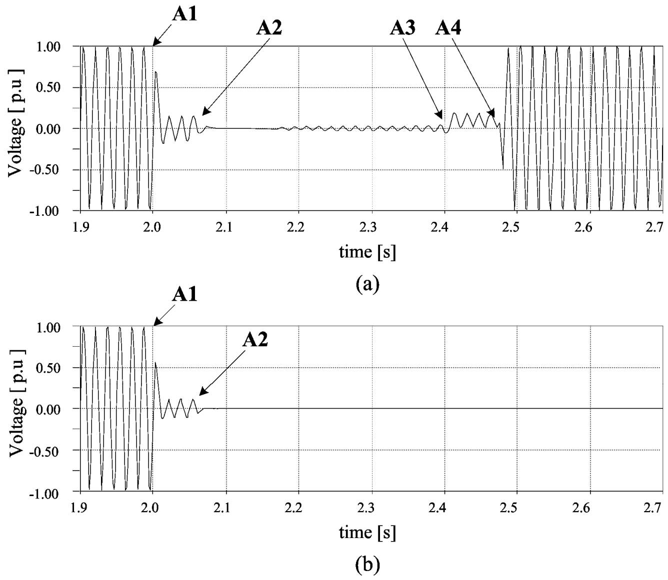

Figure 4: Voltage waveform when transient fault and permanent faults occur. (a) Transient fault. (b) Permanent fault.

Figs. 5 and 6 depict, respectively, the angle and active power of the generator under the three-phase reclosure for a three phase fault, when the adaptive reclosure and the conventional reclosure algorithms are used for the three-phase reclosure and the initial generator angle is 10°. The reclosure is activated 0.4s after the line is tripped in the case of conventional reclosure whereas the tripped line is reclosed 1.77s after the tripping of the circuit breakers in the case of adaptive reclosure. It should be noted that the relatively short dead time of 0.4s associated with the conventional approach does not take into consideration the stability aspects of the system and is solely based on a standardized prescribed time. However, in the case of the adaptive reclosure technique which also takes into consideration the system stability aspects, the dead time and therefore the time can be prolonged to a much longer period of 1.77s without threatening system stability. As discussed before, the latter is highly desirable for two reasons; (i) to increase the chance of a successful reclosure and (ii), to reduce the impact on system due to a significant reduction in reclosure transients. Figs. 5 and 6 show clearly that the angle and power oscillations are reduced and are better damped by using the adaptive reclosure, even though the dead time is increased.

Figs. 7 and 8 depict, respectively, the angle and active power of the generator under three-phase reclosure for a three phase fault when the initial generator angle is 20°. Here, the line is reclosed 0.4s after the tripping of the circuit breakers in the case of conventional reclosure, whereas 1.86s in the case of adaptive reclosure.

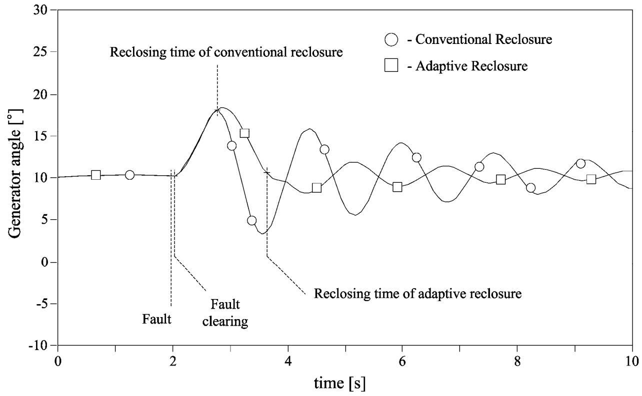

Figure 5: Generator angle when the tripped line is reclosed after the fault clearing (Initial generator angle is 10°).

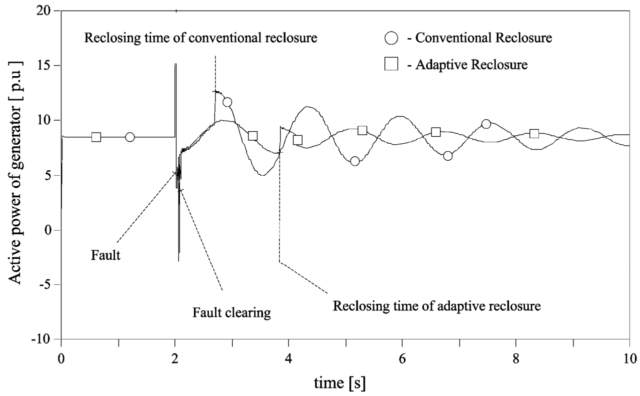

Figure 6: Active power output of generator when the tripped line is reclosed after the fault clearing (Initial generator angle is 10°).

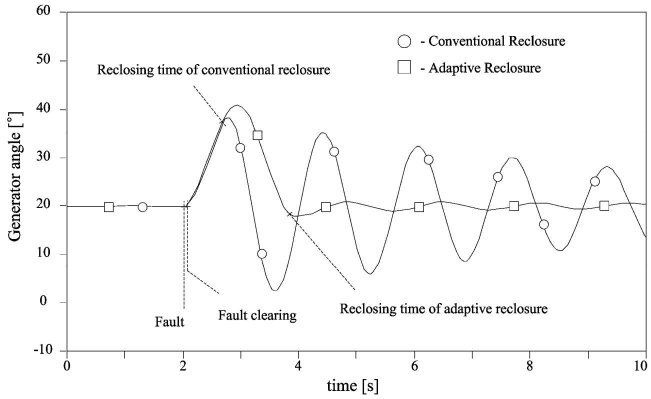

Figure 7: Generator angle when the tripped line is reclosed after the fault clearing (Initial generator angle is 20°).

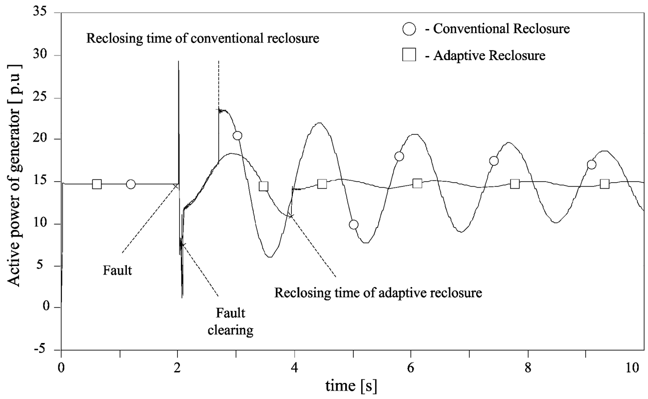

Figure 8: Active power output of generator when the tripped line is reclosed after the fault clearing (Initial generator angle is 20°).

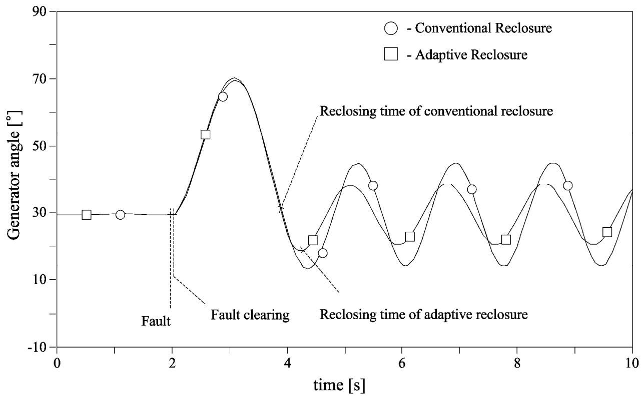

Figure 9: Generator angle when the tripped line is reclosed after the fault clearing (Initial generator angle is 30°).

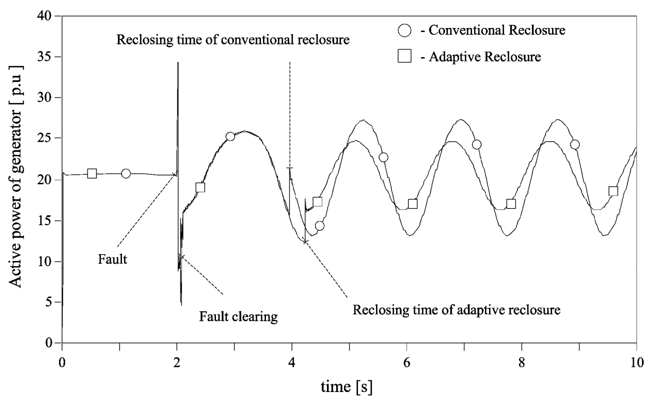

Figure 10: Active power output of generator when the tripped line is reclosed after the fault clearing (Initial generator angle is 30°).

When the initial generator angle is 30°, the angle and active power of the generator under the three-phase reclosure for a three phase fault is shown in Figs. 9 and 10, respectively. Here, the line is reclosed 1.87s after the tripping of the circuit breakers in the case of conventional reclosure, whereas 2.14s in the case of adaptive reclosure. As seen in Figs. 9 and 10, the angle and power oscillations are reduced by using the adaptive reclosure. The reclosing time of 1.87s in the case of conventional reclosure is larger than the fixed dead time 0.4s and close to the reclosing time of 2.14s for the adaptive reclosure, because the excessive SPA (standing phase angle) difference does not permit the reclosing activity and causes reclosing to be delayed during the synchro-check. Therefore, from a viewpoint of the transient stability, the synchro-check relay can offer a further advantage.

4 Conclusion

This paper has presented an adaptive autorelcosure scheme for improving the system stability. The proposed reclosure method includes the variable dead time control and optimal reclosing time. Herein, the variable dead time control scheme is used in order to distinguish clearly between the permanent and transient faults, and the optimal reclosure schemes are employed in order to prevent the transient instability. Equally importantly, the scheme has the attribute of maintaining transient stability under severe conditions such as the monotonic increment of the generator angle following a disturbance.

The simulation results show that the fault types are classified accurately by using the variable dead time control scheme, and the system oscillation is reduced and the transient stability is maintained by using the proposed adaptive reclosure method.

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